The realities of managing uncertainties surrounding pluvial urban flood risk:

An *ex post* analysis in three European cities

Abstract

Inner-city pluvial flooding is characterised by major uncertainties, often making response problematic. We explore this in London, Lisbon and Rotterdam, through ex post document analysis and semi-structured interviews. Traditional uncertainty analysis generally focuses on quantifiable factors, needing to clarify uncertainty for engineering design, flood warnings and incident management. But other uncertainties concern budgets, skills, legal issues and politics. There are also many relevant certainties or near-certainties, which can dominate. They need equal attention in understanding decision making for risk reduction. Responses to our cities' flood risks – including portfolios of engineering and non-structural measures – also contain significant no-regret components requiring less certainty about risk. Our cities appear to be positioned along a learning continuum, related to flood experience and the consequential uncertainty reduction. However progress can be worryingly slow. Only experiencing actual flood events promotes accelerated action and often the certainties concerning resource constraints also outweigh the many uncertainties in risk assessment.

Key words: Urban pluvial flooding, three cities, Europe, uncertainty, learning.

1. Introduction: Uncertainty and risk in inner-city flooding

Much pluvial flooding in inner-city areas is particularly uncertain (Takara, 2014). Its spatial extent is as unpredictable as the locations of the severe rainstorms that are its cause (e.g. Bales and Wagner, 2009). Urban 'flash' flooding - as a type of pluvial flooding - occurs very rapidly, consequent upon these rare, intense and highly localised meteorological events, often occurring in landscapes with steep topography (Gruntfest, 2009). Flood probability here is unpredictable because it is a function of those very rare events, the return periods of which are inherently uncertain because so few have been experienced at any one location in the past (Fontanazza et al., 2011). Such uncertainty can lead to difficult decision making.

Compounding this uncertainty, the performance of existing urban drainage systems is likewise unpredictable, since they are often old or subject to blockages, giving uncertain hydraulic performance (Djordjević et al., 2014). The consequences of this urban flooding can also be unpredictable, depending on where is flooded, due to highly spatially variable population densities, property and economic activity and the potential for a flood to damage key urban infrastructure that may result in disproportionate impacts. Urban populations are very mobile, if not transitory, leading to less experience of flooding, and their behaviour can therefore be unpredictable (Douglas et al., 2010).

But risk and uncertainty need differentiation. Risk is about the probability and consequences of something happening, such as a flood; certainty and uncertainty describe our state of knowledge about that happening (see also Doorn, 2014). Decision makers in urban areas are often uncertain as to future pluvial flood risk, and uncertain as to what strategy to pursue to manage this uncertain risk, which is widespread (e.g. Brandolini et al., 2012). Increased risk in the future may also arise as a consequence of climate change, changes in demographics leading to even larger cities, and accelerating urban economic activity (Beniston et al., 2007).

This paper explores the uncertainties and parallel certainties and near-certainties that are faced by urban managers, using three case studies in different European countries. We aim to see though *ex post* analysis which uncertainties can dominate and how they may or may not affect perceived solutions to the urban flooding these managers experience and the actual decisions that they may make.

2. Uncertainty in Flood Risk Management (FRM)

Uncertainty can be of epistemic origin (uncertainty as a function of a lack of knowledge), or aleatory (uncertainty in "nature") (Beven and Alcock, 2012). Only epistemic uncertainty can be reduced, but a decision maker has to contend with both.

In the field of FRM, six types of uncertainty are important:

(i) in the assessment of current and future flood risk, including its probability and consequences;
(ii) in the construction of science driven modelling and thereby the provision of information for decision making;
(iii) in the performance of existing and future measures for reducing flood risk, including peoples' response to measures a such as warnings;
(iv) regarding the type of decisions (e.g. adaptive, risk-based, robust decision making, etc.);
(v) in the communication of uncertainties in FRM and their understanding;
(vi) in the monitoring of risk and risk reduction, going forward.

In this context the choice of risk reducing measures is riddled with uncertainties (Beven and Hall, 2014; McCarthy et al, 2007). As a result, a range of uncertainty analysis methods and decision making suggestions has developed, both in this field and more broadly (e.g. Dittrich, 2016). These are intended to help decision makers "by identifying the most influential source of uncertainty, and the implications of (this) uncertainty for the preference ordering between options" (Beven and Hall, 2014, 19). Decisions often need to be made based on model results concerning future risks that come with significant uncertainty (Downton et al., 2005); this modelling is necessary because of the dearth of data showing the impacts of past events with which to assess future flooding characteristics. But attention in this type of uncertainty analysis has tended to focus on those uncertainties susceptible to modelling, and based usually on past experience rather than complete lack of knowledge, promoting the use of sensitivity analysis and similar techniques "to understand the contribution that different factors make to total uncertainty" (Beven and Hall, 2014, 19). Such uncertainty analysis (Hall and Solomatine, 2008), which in general we support, therefore has a strong focus on what can be quantified and therefore modelled (Figure 1) and on whether different mitigation options should come into play as a result of different model results (Merz et al., 2008). Peace of mind for the decision maker is maximised if the results from this modelling approach to uncertainty analysis have little or no effect on the ranking of the different options that are available and feasible for risk reduction: the uncertainty does not affect the decision to be made.

But to the decision maker there may be many sound reasons not to follow such model results, particularly when uncertainties may crucially affect the decision to be made. As Downton et al. (2005) were aware, other uncertainties and constraints may dominate decision making, including issues such as the availability of funding, the skills of the personnel available to implement their plans, the performance of their mix of existing risk reducing measures, and the receptiveness of the public to the measures suggested. If these uncertainties are outweighed by the certainties or near-certainties in any given situation, and the likely impact of the uncertainties is not too problematic, then perhaps decision making may become relatively straightforward.

3. Research approaches and methodology

Decision making under conditions of uncertainty can be approached with *ex ante* analysis, aiming to prevent poor decisions being made, and the field has been extensively reviewed and many methodologies proposed (e.g. Walker et al., 2013; Beven, 2014; Kwakkel et al., 2016; Dittrich et al., 2016). In contrast, *ex post* analysis, which has been less explored, looks at decisions that have already been made under conditions of uncertainty. Ex ante analysis answers questions such as what decisions can be made under uncertainty, with which degree of uncertainty, and how can we minimise that uncertainty. Ex post analysis seeks to answer different questions such as what decisions have been made under conditions of uncertainty, and how has that uncertainty affected this decision making. Results from ex post analysis should feed back into ex ante analysis to make a more complete presentation of the uncertainties that are factors in such decision making. As researched here, our ex post analysis aims in this way to gain insight from the past with which to help guide decisions now and in the future.

We acknowledge here the intellectual context of our work. We recognise the importance of theory-driven analysis of how actors engage with their own lack of knowledge (e.g. Gross and McGoey, 2015). However, we have found three rather more empirical approaches to describing and tackling decision making under conditions of uncertainty to be of greater value here. Thus Arentsen et al. (2000) advocate science, incrementalism and openness/learning. Raadgever et al. (2011) emphasise ignoring uncertainty, knowledge generation, interaction and coping. Kasperson (2008) promotes a strategy of delay to gather further information, targeting critical uncertainties for priority analysis, enlarging the knowledge base through lateral thinking, invoking the precautionary principle, using an adaptive management approach, and building a resilient society (White, 2008).

From these ideas we developed a simple analytical framework to better categorise and thereby better understand the role that uncertainty can play in decisions about flood problems (Figure 2). This framework identifies and classifies interrelations between reactions and responses to risk and uncertainty. Several decision strategies can of course operate simultaneously and any particular strategy may involve a combination of elements. Thus the probability aspects of urban flooding may be ignored, but the areas likely to be flooded may be mapped to reduce uncertainties in this respect. Coping with uncertainties can occur at the same time as collecting information to reduce them. The framework as in Figure 2 should not be seen as ignoring these complexities.

Our research is based on a comparison of three cases (London (Camden); Lisbon; Rotterdam), but aiming at some generalizable understanding and focussing in particular on the balance between the uncertainties and certainties in each city context. The choice of these cases was somewhat pragmatic. However, each city had to be a large EU urban agglomeration, with previous experience of pluvial flooding (but not necessarily flash flooding), and with the existence of pluvial flood management systems, but with different approaches to the problems thereby raised. Local government there had to have a role in FRM (to capture local issues), but roles vary per city. English or Dutch data sources concerning pluvial FRM decision making needed to be available to make feasible the authors' research.

But investigating decision making under uncertainty is methodologically inherently problematic: the state of knowledge and lack thereof may well be hidden or concealed. We have to rely on evaluating what decision-makers write, what they achieve in terms of outcomes, and talking to people with knowledge of the field. None of this is as straightforward as investigating situations where information is plentiful.

Our document analysis covered dozens of mainly government focused sources related to flood risk management in our three cities and their national context: directives, guidelines, laws, rules, regulations, official strategy publications, policy informing research reports, protocols, and scrutiny reports. Semi-structured interviews were conducted in Dutch or English, the authors' native languages (Table 1), and each was recorded and transcribed. Interviewees were chosen to cover as far as possible those with interests in flood risk reduction decisions (i.e. local civil servants) and their science base (i.e. the researchers in Lisbon and Rotterdam). We acknowledge that some data might be subject to differences in cultural and linguistic interpretation from interviewees to authors; for example, some interviewees in Lisbon were more comfortable speaking in English than others. We sought to manage this situation such that when two interviewees were uncomfortable in speaking English, their colleagues translated their answers for us. Also for the Lisbon case some documents were written in English but relevant passages in Portuguese were translated by one of the interviewees.

Information from both documents and interview sources was treated equally and analysed following the coding method developed by Miles et al. (2014), identifying and recording themes and sub-themes (Table 2). The data was analysed for flood risk measures taken, and those planned but not taken; the decision making rationale behind the measures; the underlying uncertainties mentioned in the sources. We compared the data and categorised it as being related to policy measures, decision making approaches and decision making rationales (Table 2). We then scored each city on each of the categories and used the results from the scoring exercise to analyse and compare the three cities' approach to uncertainty in flood risk management.

4. Urban flooding in London (Camden), Lisbon and Rotterdam

London's Borough of Camden (LBC)

Inner city Camden has a varied topography, with some steep slopes centred on Hampstead Heath creating five flood water flow pathways to vulnerable areas (Bakewell, 2008). Camden Council is the Lead Local Flood Authority, under the national Flood and Water Management Act 2010, responsible for local FRM and for implementing SUDS (Sustainable Urban Drainage Systems). Camden is also involved in London-wide FRM collaboration, such as the North London Strategic Flood Risk Assessment (Bakewell, 2008). The privatised Thames Water is responsible for the installation and maintenance of the urban storm sewerage network, whilst in the UK the FRM governance system is dominated by general oversight by the Environment Agency under the 2010 Flood and Water Management Act, working to policies formulated by the Department for Environment Food and Rural Affairs (e.g. Defra, 2009; 2011), strongly influenced by a cost:benefit imperative derived from the UK Treasury's insistence on best value for money (e.g. Penning-Rowsell et al., 2013). Parallel UK policies stress careful spatial planning in flood risk areas, and national/local cost sharing.

Flash flooding in Camden from extreme rainfall poses a high to very high risk (LBC, 2003) not least because of the Borough's old drainage system. In 2.5 hours in August 1975 150mm of rain fell in a relatively restricted area. The 2002 event was less severe (60mm in less than one hour). Both flooded parts of Camden, disrupting public services and causing damage to properties, businesses and schools; one person died in 2002 and some citizens had to vacate their homes (LBC, 2003). A Scrutiny Panel was set up following the 2002 event, making recommendations for further measures (LBC, 2013), the extensive documentation from which meant less reliance here on interviews.

Camden's approaches to uncertainty

Within its five guiding principles for FRM (LBC, 2013: 8), two relate to uncertainty. First, gathering further information is central: "Improving the level of knowledge about flood risk across all stakeholders is a vital process which needs to be continued" (LBC, 2013c: 9) and "Decisions on where local resources are focused should be evidence-based and made against clear criteria". Flood risk maps have been developed, with other north London Boroughs, but the two events experienced in the last 40 years are insufficient for estimating return periods and adequate risk mapping. Being therefore reliant on flood modelling, Camden has developed and relied on new purpose-built models and the science that underpins them. But one interviewee commented that, despite much effort, "It has been difficult to say with certainty the level of risk in the way we would like … (But) we spent quite a lot of time and money … to develop new models and … we (now) feel more confident where the flood risk is".

Secondly, delaying action until targeted knowledge acquisition provides less uncertainty is also an adopted approach - although not explicitly mentioned in any policy document. Evidence-based decision making selects targets "where local resources are (to be) focused" (LBC, 2013: 9): there has to be sufficient certainty about costs, benefits and the effective performance of any new measures before decisions can be made. An interviewee reflects on this strategy: “It is very hard to find schemes which (the evidence shows) will protect enough properties to make the whole thing worthwhile”. This evidence based approach is also reflected in spatial planning policies for new developments, which can only proceed after full information is presented about flood risk from the development in the neighbourhood and the impact on its drainage system.

Although seeking to create a resilient society is not part of Camden’s formal approach to uncertainty, the Borough relies heavily on flood recovery through the near-universal private sector based insurance of home owners and companies. Citizens are also encouraged to sign up for the Camden Alert Service, giving flood warnings via mobile phones. The Borough is postponing the installation of new infrastructure such as permeable roads and enhanced drainage capacity until those systems need replacement. This is a money saving no-regret approach, and type of decision making, given that infrastructure renewal is a continuous urban process. Adaptive management itself has not, however, been formalized. The Greater London Authority (GLA) has facilitated learning between Boroughs, and developed pilot pluvial FRM projects, such as for implementing community flood plans. In spite of these learning mechanisms, there are no high levels of adaptability embedded in decision making here. Moreover, the precautionary principle is not apparent in Camden’s approach. On the contrary: whilst modelling has progressed, the Council has tended to wait for strong proof of harm before implementing measures to manage its flood risk.

Measures coping with or reducing the risk

Faced with the uncertainties inherent in FRM prioritisation, Camden has adopted a risk-based strategy to address pluvial flood risk, targeting critical at-risk areas. The Borough’s second strategy is to encourage the use of SUDS to reduce flood risk (LBC, 2013). Structural measures and schemes are being explored but have not yet been implemented.

To tackle flood risk, Camden mainly relies on spatial planning, focusing on curtailing risk build-up. All new developments reducing the area of permeable surface require a drainage assessment and provide compensation for this loss. Basements can only be developed following a drainage and flood assessment and may not be inhabited in the floodable areas. Camden has created a hierarchy of SUDS options, with impermeable surfaces and infiltration being the preferred option, and direct discharge into a combined sewer the least favoured. However, apart from the King’s Cross train station development, no major SUDS have been installed.

The Borough’s citizens are only moderately involved, although flood insurance penetration rates are relatively high at c. 85% (Surminski et al., 2014). The Environment Agency has extensively researched flash flood risk (Environment Agency, 2007) and localised convective rainfall events are forecast probabilistically so that decision makers can anticipate flash flooding situations. But there is no specific Camden programme to reduce the current risk of flash flooding and our interviews showed that many risk communication issues remain.

Lisbon

The Portuguese Environment Agency (APA) is responsible for FRM in Portugal, with an overview from the National Commission for FRM (CNGRI). Urban flash and pluvial flood risk is primarily managed by municipalities - through their Civil Protection Departments – together with their responsibilities for urban planning, flood mapping and flood risk management plans. National standards have to be met and resources are distributed nationally, apparently with some lack of attention to local situations (Pedro Pinto dos Santos et al., 2014).

Lisbon is prone to pluvial flooding due to heavy convective rainfall (Fragoso et al., 2010) on a city centre that is relatively old, with a drainage system that has blockages creating performance uncertainty; serious flood events occurred in 1983, 1997, 2008, 2010 and 2014. The disastrous flash flooding in 2008 (Fragoso et al., 2010) occurred when 118.4mm of rain fell in 24 hours, with an hourly maximum of over 30mm. The event caused four deaths and damaged many houses and much infrastructure.

Lisbon's approaches to uncertainty

Regarding uncertainty, the municipality of Lisbon is undoubtedly aware of the problem of pluvial flooding and flash flooding. The uncertainty with flash flooding here mainly lies in the limited predictability of any particular up-coming flood event rather than uncertainty about the current and future risk of flooding *per se*. One interviewee reflected: "We have defined the problem and we know the critical areas".

However, all our interviewees felt that Lisbon is not addressing the problem sufficiently, particularly regarding flash flooding and urban planning: "We don't do anything". However, this non-action is not a result of uncertainties surrounding the problem. Rather, political differences and inadequate budgets are the constraining factors. Consequently Lisbon has adopted a strategy of knowledge acquisition with regard to key uncertainties. It has long experience with creating flood risk maps to increase knowledge and communication about critical areas. Information is also sought from informal channels when there is uncertainty about a flooding problem or its risk. For example, the Civil Protection Department of the municipality (CPD) turns to universities for extra weather forecasts, because the national Meteorological Office has not provided adequate hourly precipitation forecasts.

No-regret measures are not an integral part of Lisbon's approach to uncertainty, although one practice may be characterised as such: by planning and restructuring parks upstream of the city's valleys, Lisbon's *Green Plan* has a key aim of reducing runoff (Municipality of Lisbon, 2010). The invocation of the precautionary principle is also not apparent in Lisbon's management strategies, and there is little evidence of an adaptive management approach, although steps are taken to implement a learning system. A Local Emergency Preparedness Plan has been initiated in the city centre and best practices will be implemented in other areas (Municipality of Lisbon, 2013).

But Lisbon is seeking to rely on a resilient society approach. Uncertainty with regard to budgets, politics and the uncertain and sudden nature of flash flooding provide a context for developing that approach, so one interviewee commented: "People know [that floods have] happened this year and are likely to occur next year. They have put in place their own protection (measures) …. to avoid water coming in". Local communities, employees and children are supported by the CPD to increase their resilience to natural hazards through risk communication campaigns and community visits. The private insurance system is also seen to contribute to resilience, although participation is voluntary and penetration rates are only c. 50% (Surminski et al., 2014). For people to respond well, the weather forecasts and flood warnings are communicated deterministically. An interviewee observed: "There is a feeling that probabilities are not yet the best way to tell people".

By joining the United Nations 'Making Cities Resilient' campaign, Lisbon has formalised the approach of creating a resilient society (Municipality of Lisbon, 2013). However, one interviewee was sceptical: "Lisbon is a resilient city within the UN. But when they ask if Lisbon is getting ready, we say we have too many other priorities. We have no money. We only have ideas".

Measures coping with or reducing the risk

In terms of pluvial flood measures Lisbon appears to have has no leading strategy or vision to underpin its FRM policies; the many uncertainties may assist in retaining this *sotto voce* approach. Its FRM portfolio consists of a combination of understanding risk, warning systems and relying on people's response to flood events. Structural measures to protect vulnerable areas against flooding have not been taken up by the municipality, neither is FRM integrated with urban planning. Here one interviewee commented that "bad management (of spatial planning) increases the risk of flooding".

Upstream retention basins and 'greening' the surface area have been planned, but not yet implemented. Moreover, changes to the drainage system are only made when the system is malfunctioning, as part of general maintenance. No large-scale restructuring of the sewerage and drainage system has been planned (Municipality of Lisbon, 2013). Instead, as indicated above, citizens are expected to take responsibility for flood preparedness. A system is in place to warn the CPD, who can alert emergency services, businesses and citizens. But one civil servant responded that only "more or less half of the population knows that we have floods and how to act". This is despite considerable attention being given to informing citizens and businesses at the start of each hydrological year, encouraging them to flood-proof their buildings.

Rotterdam

Compared with Camden and Lisbon, Rotterdam is a flat city, without the steep topography generating significant flash flooding. However, it is located below sea level, with consequences for free drainage. Land subsidence has also created low spots for flood water to accumulate (Goedbloed, 2013). Moreover, some waterways have been filled in, reducing permeability, water pathways and storage, making the city centre highly susceptible to rainfall, although previous flood mitigation arrangements have been replaced by a large capacity drainage and pumping system, for which the municipality is responsible (Municipality of Rotterdam, 2011).

The city experienced pluvial flooding in 1999 and 2001. On 18 August 2001, water flowed into basements, offices, shops, roads and tunnels in the city centre (Pieneman and Goedbloed, 2014). 'Flash flooding' is an unfamiliar term in Dutch terminology, possibly owing to the lack of steep slopes in Dutch landscapes, but all future climate scenarios predict more extreme rainfall events in the Netherlands, and more such events have been observed (Van den Hurk, Siegmund and Klein Tank, 2014).

The Dutch government has set inundation norms for urban flood risk. As defined by National Administrative Agreement on Water (2003), urban areas may inundate from a 1:100 year pluvial flood, markedly different from much more stringent norms for river and coastal flooding (up to 1:10,000 years). Provinces are responsible for the transposition of national norms and, for Rotterdam, the Province of South Holland adopted the 1:100 year norm in its 2009 Water Regulation. But in such urban areas the Municipality is responsible for the drainage system and urban planning. Rotterdam is covered by three Water Authorities who manage the (main) water system and monitor the spaces for water storage. In practice these authorities and the Municipality work closely together in creating water plans, urban plans and meeting the inundation norms.

Rotterdam's approaches to uncertainty

Despite much uncertainty - or perhaps because of it - Rotterdam appears to have a clear plan. Gathering information is one of the pillars in Rotterdam used to adapt to climate change and to reduce uncertainty (See: De Snoo, 2014; Municipality of Rotterdam, 2013a). But gathering more information has not been a rationale for delaying action to reduce current pluvial flood risk. Rather, knowledge has accumulated in conjunction with pilot projects, with the 1:100 norm as an incentive. Nevertheless, the uncertain return periods of extreme rainfall due to climate change has been a justification for postponing further action to increase water storage capacity or to implement other measures.

Knowledge acquisition is focused on reducing critical uncertainties in flood risk modelling and forecasting. The city and water authorities are continuously monitoring the water drainage system to understand its functioning and capacity, helping to improve flood risk models. Rotterdam has participated in the RainGain research project, installing radars and rain gauging stations with the aim of improving the prediction of pluvial flooding as flow gauging cannot yet identify flooding at neighbourhood or street scales.

Advancing knowledge is also part of the city's adaptive management approach (Municipality of Rotterdam, 2013b). The city had adopted the universal norm-driven strategy, aiming to create sufficient water storage to protect against a 1:100 year flood, as required by law. But the Water Plan of 2007 was revised in 2013 because of new developments and knowledge (Municipality of Rotterdam, 2013a): less water storage is needed than initially calculated and drainage bottlenecks and hence system performance is now better understood. Instead of aiming to reach the 1:100 norm as efficiently as possible, regardless of critical areas that more frequently flood, Rotterdam now prioritises areas most in need of increased storage, helped by the Dutch government postponing meeting the norm to 2027 (Government of the Netherlands, 2011).

Another pillar of Rotterdam's adaptive management is 'learning'. The adaptation strategy sees Rotterdam as "a showcase and laboratory for innovative adaptation strategies" (Municipality of Rotterdam, 2013b: 30). An example is the creation of 'water plazas' intentionally inundated during heavy rainfall events. But there are limits to Rotterdam's adaptability: nearly all measures are engineered and cannot easily be reversed. Responding to this acknowledged inflexibility, Rotterdam opted for a phased implementation of innovative infrastructure to allow for experimentation, monitoring and learning (Goedbloed, 2013).

No-regret measures are also important here (Municipality of Rotterdam, 2013b). Encouraging companies and residents to install green roofs and replace pavements with plants are examples. To improve water storage and drainage, Rotterdam relies on future development projects and future replacement of piped and paved infrastructure. The last approach uses the precautionary principle, which is invoked for events less extreme than 1:100 years. The residual risk is captured by a 'safety net' of non-structural measures, such as a warning system and emergency planning, although flood insurance is very uncommon. For future flood risk reduction, the city relies on the same protection norm, but it anticipates adjusting this after 2030 (Goedbloed, 2013)

Measures coping with or reducing the risk

Rotterdam aims to become "climate proof" by 2025, and "water proof" by 2030 (Municipality of Rotterdam, 2013b), with special attention to the expected future increase in extreme rainfall events and a reliance on detailed weather forecasts.

In line with traditional Dutch FRM, Rotterdam relies on engineering measures to manage pluvial flood risk (Surminski et al., 2014), driven by the legal minimum protection norm, measured by the water storage capacity of structural measures. Rotterdam aims to increase water storage independent of the existing drainage system, such as in the 'water plazas' or in underground water storage in densely developed areas without the space for spatial planning measures. The Second Water Plan favours outdoor measures integrated in spatial planning, such as canals and green areas.

By improving models, from greater attention to their underlying science, the city has now identified priority areas vulnerable to lesser than 1:100 year flood events. Additionally, the city aims to raise public awareness about citizen responsibility in FRM by incentivising them to implement small structural measures, such as the green roofs and increasing garden permeability. However, public awareness is low, as one interviewee commented, because "the Dutch rely on Government to protect their homes from flooding". There are no measures that particularly address pluvial flood risk, but the warning system was adjusted in 2004 and 2011, owing partly to poor forecasting of convective rainfall. Communicating with probabilistic warnings some days in advance allows for timely preparation for extreme one-hour precipitation events that can lead to flooding.

5. Assessment

Similarities and differences

Our three cities clearly rely on different FRM approaches (Table 3) and each uses a portfolio of measures, including structural measures, non-structural measures and insurance (excepting Rotterdam regarding insurance).

All three cities seek to advance knowledge – obviously tackling epistemic uncertainty - to better understand pluvial and flash flood risk to address their acknowledged uncertainties (Table 3); there is no evidence of non-action owing to these uncertainties. But all three have pluvial flooding experience, albeit with different intensities, making to ignore or deny the risk an improbable decision strategy. Elsewhere it might well be different, such as where only model results are available for assessing risk, and there is no significant history of flooding.

However, faced with the kind of uncertainties we have described, the decision strategies diverge (Table 4). Camden is predominantly focussing on advancing knowledge, with little adaptive management. Rotterdam has a multitude of approaches, but leads with adaptive management. In contrast, Lisbon has not fully adopted any one approach, tending towards seeking to create a more flood-resilient society. However, our results are a snapshot in time. So, for example, Camden has been in the midst of formulating and implementing measures to address pluvial and flash flood risk; more explicit policies may come with more solid cost-beneficial FRM measures, or from learning from other cities. Lisbon's civil servants are waiting for a window of opportunity to gain political support and budgets for flood risk measures; Rotterdam's adaptive management may lead to different approaches than those initially adopted.

Decision strategies appear to follow a sequence of uncertainty-related steps (Figure 3). Camden is at the stage of advancing knowledge, whereas Rotterdam has passed this stage and is now at the experimental stage, assessing coping strategies. Other cities will all be positioned somewhere on this sequence. However, the sequencing process is not rigid, as the case of Lisbon highlights, but can involve moves back and forth over the several steps, and may never progress at all. What is achieved may follow 'fashions': Rotterdam has adopted 'modern' measures (e.g. the water plazas), whereas London (Camden) and Lisbon are conventional in their approach to decision making under uncertainty, or perhaps are further back in the stepped sequence. Probabilistic forecasting is another 'fashion', with the UK Meteorological Office being a first mover. Moreover, approaches may change if practice shows that a strategy deals with uncertainty inadequately because it has a major aleatory element that resists its minimisation through knowledge enhancement.

Near certainties

Our interviewees acknowledged that the flood risk problem they faced was not completely uncertain and that they worked with certainties too, several of which are susceptible to modelling and should be included anyway within any uncertainty analysis. Thus where there are steep slopes, substantial paved areas, reoccurring seasonal drainage blockages, low spots where floodwater can accumulate, in a location with intense summer convective rainfall, then damaging flash flooding is possible, if not likely (the Lisbon situation). Some cities have well defined flow pathways towards one particular low area; Lisbon makes use of this knowledge, as implicitly does Rotterdam.

With some history of heavy rainfall causing flooding, the degree of uncertainty again diminishes (i.e. Camden; Lisbon). Where the sewerage is dilapidated or inadequate, or with blockages, or when that system's outfall is tide/river level locked, then dangerous flooding may be likely: hence Rotterdam's safety related priorities. The overall condition of the system may be well known and one Lisbon interviewee said that autumn blockages are more likely owing to leaf fall. In addition, the nearer we get to a flash flooding event (say 1-4 hours before), the more certain we are about its timing, location and intensity.

Each city relies on the certainty that all infrastructure (roads and drainage systems), has to be continually maintained and replaced; delay does not necessarily mean inaction. Moreover, the uncertain weather forecasts were perceived by seven Lisbon interviewees as a certainty that decision makers have to anticipate, for example by using probabilistic forecasting or alternative information sources. The scenario of increased frequency of heavy rainfall in the future as a result of climate change is also perceived as a certainty (Goedbloed, 2013; LBC, 2013).

Certain other uncertain factors

Our interviewees and policy documents also revealed a number of other factors, enumerated below, that influence decision making which may be more decisive '(un)certainty factors', none of which is currently susceptible to the type of quantification based modelling and uncertainty analysis that has become common. This is not to deny the importance of such traditional uncertainty analysis, but it cannot cover all uncertainties and may well not include those dominating the decision maker.

Firstly, *finance* is an important certainty or uncertainty at any one time, although episodic finance can incentivise experiments with pilot projects, providing learning. Camden has refrained from adopting risk reducing measures, because, as one interview commented, the cost-benefit analysis result was not approved. In Lisbon, inadequate finance is also a major obstacle to implementing FRM measures. In contrast, Rotterdam regularly has budgets for adapting to pluvial flooding as an effect of climate change. Additionally, it treats FRM as an economic resource: its experimental approach (producing learning) has become a showcase for promoting the city and an export earner for Dutch (engineering) companies.

Secondly the *legal context* can be crucial. Rotterdam has been legally tied to the 1:100 year norm, incentivising structural measures; Camden and Lisbon had legal incentives to produce flood risk maps, leading to further knowledge generation. Interestingly, no respondent judged that the EU Floods Directive had a direct impact by creating legal obligations, but had catalysed the consideration of coping measures.

Thirdly, *politics* plays an important role, a finding here that is far from new but which remains important. The majority of interviewees felt Lisbon's mayor did not prioritise flood risk and climate change impacts, whereas in Rotterdam the political agenda-setting of climate change adaptation facilitated the prioritisation of pluvial flood risk reduction there.

Fourthly, the information we gathered indicated that the *cultural context* also can determine the approach and measures adopted, alongside the many uncertainties. In Rotterdam this operated in two ways: the Dutch traditionally rely on engineered infrastructure to manage flood risk, and a flood event could harm the reputation of Rotterdam and the Netherlands as a flood resistant society, at an economic cost. The UK has a culture of flood insurance (Penning-Rowsell et al., 2014), enabling Camden to delay major FRM decisions until they are known to be cost-beneficial, relying on home owners to take some responsibility for their own protection and recovery. Lastly, Portugal has long experience with civil protection from natural hazards, such as earthquakes, forest fires and floods. Unsurprisingly its FRM strategy focuses on preparing its citizens for hazards and their consequences.

Finally, there is a strong element of *path-dependency* in urban development that shapes decision strategies with regard to pluvial FRM and its uncertainties. The set of possible decisions to be made today and in the future is limited by the decisions that have been made in the past, even though past circumstances may no longer be relevant. Thus virtually all major cities have an old centre where the risk of pluvial flooding can be relatively high, but where it is difficult and expensive to alter drainage systems or change urban layouts, thus limiting the range of feasible risk management options. Rotterdam and Lisbon were able to consider some flood risk reduction measures in suburban areas to relieve their city centres, but for inner-city Camden this is not an option.

6. Conclusions

The risk of flooding in the future is undoubtedly surrounded by uncertainty, and urban pluvial floods are perhaps at the centre of this web of uncertainties. Yet decision-makers today have to make decisions on the basis of incomplete knowledge.

We believe our ex post analysis, with its combination of document analysis to study the written policies of the three cities and interviews to highlight issues and problems in decision making, has made a start in illustrating a wider range of uncertainties (and some complementary near-certainties) than is foregrounded in the current general understanding of and approach to uncertainty in the traditional flood risk management literature. We suggest, as a result, that to help flood risk decision making under uncertainty we should also seek to address the extended categories of uncertainties which we found in our research in our three cities and try to minimise them or perhaps seek to model them more fully in ex ante analyses.

Much could be learned, moreover, from further *ex post* research on other cities, but we can see from our three case studies that managing the many uncertainties regarding urban flooding is complex, and that many important aspects will never be quantified so model development and formalised uncertainty analysis will never be easy or all-encompassing.

But, deployed in parallel, *ex post* analysis as a methodology, as used here, appears to be valuable in teasing out some of the reactions and consequent responses to urban flood risk and the unquantifiable uncertainties that affect plans and action. We recognise that such analysis needs further exploration, perhaps in further examples in contrasting circumstances, to fully understand and unpick these uncertainties, identify certainties and near-certainties in so far as each of these affect possible decision strategies.

Notwithstanding this need for further examples, from what we have already seen in our three cities there is at least some fair understanding of uncertainty in the urban management system (including, we infer from our documentary research, in the public) related to flooding. Even without any modelling this understanding can trigger reactions – but does not guarantee to do so - which in turn lead to responses and actions to reduce flood risk. Some sensible decisions can thereby be made despite much uncertainty, such as no-regret strategies and measures implemented in the normal process of periodic urban infrastructure replacement and renewal. In this respect learning from other cities will pay dividends for those lagging behind, and we see this as related to a city's position and possible movement on the learning continuum we have described.

However progress can be worryingly slow in relation to current and possible future levels of risk. This is principally because, first, rapid movement along that continuum unfortunately appears unlikely without experiencing actual flood events and, secondly, because in many if not most cities key resource constraints rather than uncertainty will often constrain decisions on major risk reducing plans and their actual implementation.

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Table 1
*The interviews: numbers 1-12 face-to-face, telephone or skype; numbers 13-17 by e-mail**

Occupation/role/institution	**Case study**
1. Researcher – University of Lisbon	Lisbon
2. Civil Servant - NACP	Lisbon
3. Civil Servant - IPMA	Lisbon
4. Civil Servant - CPD	Lisbon
5. Civil Servant - CPD	Lisbon
6. Civil Servant - CPD	Lisbon
7. Civil Servant - CPD	Lisbon
8. Researcher – University of Lisbon	Lisbon
9. Researcher - KNMI	Rotterdam
10. Civil Servant - HHSK	Rotterdam
11. Researcher – TU Delft	Rotterdam
12. Civil Servant – Camden Council	London (Camden)
13. Civil Servant – Municipality of Rotterdam	Rotterdam
14. Employee - Thames Water	London (Camden)
15. Researcher – TU Delft	Rotterdam
16. Civil Servant - Rijkswaterstaat	Rotterdam
17. Civil Servant – Greater London Authority	London (Camden)

NACP – Portuguese National Service of Civil Protection
IPMA – Portuguese Sea and Atmosphere Institute
CPD – Civil Protection Department, Lisbon
KNMI - Royal Netherlands Meteorological Institute
HHSK - Schieland en de Krimpenerwaard Regional Water Authority
* The number of interviewees, selected with 'purposeful sampling' (Longhurst, 2003) for their experience and expertise related to pluvial flooding, is not equal in the three cases because some had many more policy documents to provide the relevant information.

Table 2
Themes and sub themes used in the data analysis

Themes		
Policy measures	Decision making approach to risk and uncertainty	Decision making rationale
Sub-Themes		
Structural measures Non-structural measures Recovery Gathering knowledge	Non-action: problem is unknown Non-action: problem is uncertain Delay action to gather further information Action based on precautionary principle Target knowledge acquisition on critical uncertainties to focus action No-regret action Adaptive management Building a resilient society	Epistemic uncertainty Cultural Legal Political Path dependency in urban development

Table 3

A summary evaluation of measures for coping with pluvial and flash flood risk

		Camden	Lisbon	Rotterdam
Structural measures	Engineered	◆◆◆	◆◆	◆◆◆
	Urban planning	◆◆	◆	◆◆◆
Non-structural measures	Forecast & warning	◆◆	◆◆◆	◆◆
	Emergency plan	◆◆	◆	◆◆
	Public involvement	◆	◆◆◆	◆
Recovery	Insurance	◆◆◆	◆◆	◇/◆
	Networks	◆	◆◆	◇
Advancing knowledge	Research	◆◆	◆◆	◆◆◆
	Understanding risk	◆◆◆	◆◆	◆◆

◆◆◆	The pluvial flood risk measure is planned, implemented and enforced to address pluvial flood risk. It forms an integral part of the city's FRM strategy. Compared with other measures, this measure is of relatively high importance to the overall FRM strategy.
◆◆	The pluvial flood risk measure is planned, implemented and enforced to address pluvial flood risk. The measure is one of a range of measures in the FRM portfolio.
◆	The pluvial flood risk measure is planned, taken up on a voluntary basis, or there is evidence of one or a few practical examples of the implementation of this measure. However, implementation is not crucial to the city's pluvial FRM strategy and/or enforcement is not stringent.
◇	No element of the pluvial flood risk measure is present in practice, nor is the implementation of this measure intended or planned.

Table 4

A summary and evaluation of approaches to addressing uncertainty regarding pluvial and flash flood problems. The dashed boxes indicate the most important decision strategies.

<u>Reaction</u> to uncertainty and <u>response</u> to flood problem	**Decision strategy**	**Camden**	**Lisbon**	**Rotterdam**
Reducing uncertainty and coping with flood risk	Building a resilient society	●	●●	●
	Adaptive management	○	●	●●●
	No-regret measures	●●	●	●●
Ignoring uncertainty and coping with flood risk	Precautionary measures	●	○/●	●●
	No-regret measures	○	○	○
Reducing uncertainty and no flood risk reduction	Delay action to gather further information	●●●	○	●
	Target knowledge on critical uncertainties to focus action	●●	●●	●●
Ignoring uncertainty and no flood risk reduction	Non-action: problem is uncertain	○	○	○
	Non-action: problem is unknown	○	○	○

●●●	The approach is formally adopted by decision makers in laws, regulations, policies, statements or formal communication. Policy practice has demonstrated that the approach is adopted coherently and (close) to its full potential, e.g. by adopting a complete portfolio of measures in line with the approach.
●●	The approach is formally adopted by decision makers or there is clear evidence that this approach is intended. Policy practice has not demonstrated that the approach has been adopted to its full potential, but there is evidence of some practical cases of the approach.
●	Some elements of this approach are present in practice, for example by adopted policies that reflect the spirit of the approach. However, this approach is not consistently and coherently extended to other practices or formally adopted by decision makers. It may just be a single case.
○	No element of this approach is present in practice, nor is the adoption of this approach intended or formally adopted by decision makers.

Figure 1

Hall and Solomatine's (2008) uncertainty analysis framework, predominantly tackling quantifiable uncertainties (i.e. the "evidence", line 2, and the quantifying "functions", line 3)

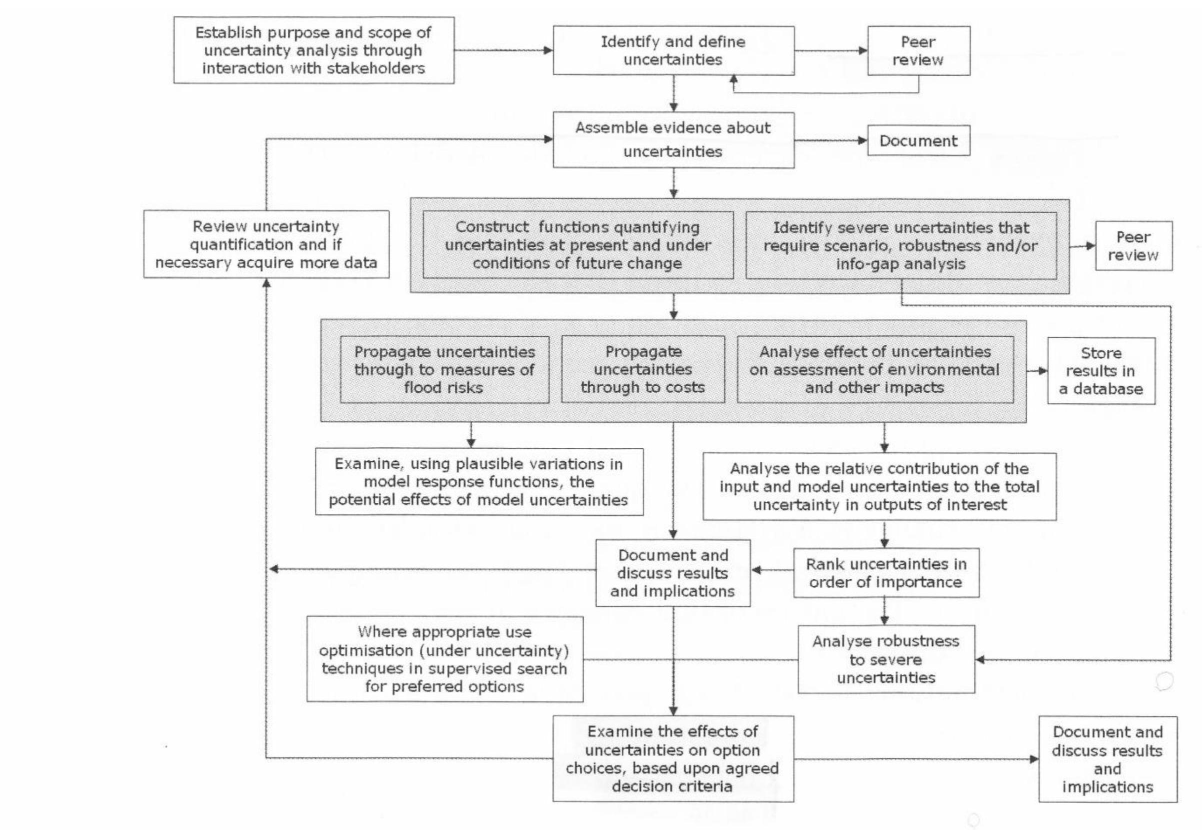

Figure 2

A simple typology of decision strategies linked to reactions and responses to uncertain flood risk management issues

Reactions to uncertainty about the flood problem	**Responses to the flood problem** No risk reducing action	 Active risk reduction/coping
Ignoring uncertainty	The flood problem is unknown or the flood problem and uncertainties are ignored. *Decision strategies:* • *Non-action*	Uncertainty is ignored, but the flood problem is being coped with. *Decision strategies:* • *No-regret measures* • *Precautionary measures*
Reducing uncertainty	Uncertainty is reduced, but the flood problem is not being coped with or action is delayed. *Decision strategies:* • *Delay action to gather further information* • *Target knowledge on critical uncertainties*	Uncertainty is reduced and the flood problem is being coped with. *Decision strategies:* • *No-regret measures* • *Adaptive management* • *Building a resilient society*

Figure 3.

A schematic of our three cities' positions in terms of reactions to uncertainty and response to their pluvial flood risk.